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Upper bound on the mass scale of superpartners in minimal $N = 2$ supersymmetry

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Abstract

If $N = 2$ supersymmetry breaks to $N = 1$ supersymmetry at an intermediate scale m_2 and then, later on, $N = 1$ supersymmetry breaks and produces standard model at a scale m_{susy} such that $m_2 > m_{susy}$, renormalization group evolution of three gauge couplings are altered above the scale m_2, changing the unification scale and the unified coupling. We show that when we enforce this general condition $m_2 > m_{susy}$ on the solutions of the renormalization group equations, the condition is translated into an upper bound on the scale m_{susy}. Using presently favored values of $\alpha_1(m_z), \alpha_2(m_z), \alpha_3(m_z)$, we get $m_{susy} < 4.5 \times 10^9$ GeVs for the central value of $\alpha_3(m_Z)$. When low energy threshold effect is present, this bound gets smeared yet remains generally stable in the $10^9 - 10^{10}$ GeV range. We also show that if we demand string unification instead of having an unified gauge theory, this constraint can be changed by exotic hypercharge normalizations.

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In minimal supersymmetric standard model (MSSM) there exists a fundamental scale m_{susy}. It is a common mass scale of the superpartners of Standard Model(SM) fields. We usually assume that it is less than a TeV or so because it helpful for solving the gauge hierarchy problem. In principle m_{susy} can be as high as the Planck scale or the String scale. In this paper we will seek an upper bound on the scale m_{susy} by demanding that gauge couplings should unify at some scale M_X, and there exists a natural hierarchy of four mass scales of the form $M_X > m_2 > m_{susy} > m_z$. Here m_2 is the scale where $N = 2$ supersymmetry breaks, all mirror particles of MSSM become heavy and they decouple from Renormalization Group(RG) running. As in usual notation m_{susy} is the scale where super partners of Standard Model becomes heavy and so they decouple from RG running. Therefore we see that m_{susy} is the scale where $N = 1$ supersymmetry breaking is expected to be directly felt by experiments[1, 2, 3, 4, 5, 6, 7], consequently it is quite important to search for any theoretical upper bound that may exist on the mass scale m_{susy}.

Supersymmetric extensions of the standard model are interesting from two points of view. (i) Gauge coupling unification is precise at the scale of approximately 2×10^{16} GeV[8, 9, 10, 11]. (ii) Divergences in the scalar sector are canceled by loops involving superpartners of standard particles which helps to solve hierarchy problem partially[17, 18, 19]. $N = 2$ supersymmetric extensions of the standard model are relatively less studied[1] even-though they are much more restrictive than the $N = 1$ framework. Particularly after the breakdown of $N = 2$ supersymmetry, vanishing of supertrace $Str(M^2)$ condition forces all field dependent quartic divergences to be zero[20, 21, 22, 23], which is a desirable ingredient for solving the hierarchy problem in a more comprehensive manner. There are known mechanisms by which $N = 2$ supersymmetry can be spontaneously broken down to $N = 1$ in local quantum field theories. It is therefore relevant to consider a symmetry breaking chain in which $N = 2$ supersymmetry is spontaneously broken at an intermediate scale below the unification scale. This possibility is studied by Antoniadis, Ellis and Leontaris (AEL) [24]. In their analysis AEL assumed $m_Z \equiv m_{susy}$, or in other words minimal supersymmetric standard model is effective very near the electroweak scale. Consequently they used $N = 1$ beta functions from the electroweak scale and the intermediate scale and $N = 2$ beta func-

[1] In extra-dimensional models N=2 supersymmetry occurs frequently. See for example [12, 13, 14, 15, 16]

tions from the intermediate scale to the unification scale. In this present analysis we separate m_Z from m_{susy} and make m_{susy} a free parameter and then we run couplings up to the scale m_{susy} using non-supersymmetric beta functions, from m_{susy} to m_2 we use $N = 1$ supersummetric beta functions as was done by AEL and from m_2 to the unification scale M_X we use $N = 2$ supersymmetric beta functions exactly as AEL performed. We aim to obtain constraints on the scale m_{susy} enforcing two conditions (a) gauge coupling unification should take place (b) The condition $m_2 > m_{susy}$ has to be satisfied. We will see that in this way we can obtain an interesting upper bound on m_{susy}. This the result that we are reporting in this paper.

We know that if $N = 4$ supersymmetry is present, beta functions vanish at all orders[25, 26, 27, 28, 29], but if $N = 2$ supersymmetry is present, they vanish beyond one-loop order[30, 31, 32, 33, 34]. For $N = 1$ supersymmetry, however, using one loop beta functions is an approximation. This approximation is justified in the context of the present analysis. Had we done a precision test of whether gauge couplings are at all unifying or not in a restrictive scenario like unification in MSSM it would have been necessary to use higher loop beta functions. However, our objective is not to do a precision test of gauge coupling unification. We will give an upper bound on the scale m_{susy} is a theory with two intermediate scales namely m_{susy} and m_2; one does not gain appreciably in precision by using higher loop beta functions in a theory with many unknown intermediate scales. Using two loop beta function below m_2 will give a slight shift in the values of m_{susy} and m_2. Because we have to cross two thresholds m_2 and m_{susy}, and we are neglecting unknown threshold effects at those intermediate scales, it is reasonable to neglect two-loop corrections to gauge coupling evolution which is comparable to these threshold corrections.

The three gauge couplings evolve via the Renormalization Group Equations (RGE). The solutions of RGE in the energy range $m_Z \longrightarrow m_{susy} \longrightarrow m_2 \longrightarrow M_X$ are,

$$\alpha_1^{-1}(m_Z) = \alpha_X^{-1} + \frac{\beta_1^{N=2}}{\kappa} \ln \frac{M_X}{m_2} + \frac{\beta_1^{N=1}}{\kappa} \ln \frac{m_2}{m_{susy}} + \frac{\beta_1}{\kappa} \ln \frac{m_{susy}}{m_Z}, \quad (1)$$

$$\alpha_2^{-1}(m_Z) = \alpha_X^{-1} + \beta_2^{N=2} \ln \frac{M_X}{m_2} + \beta_2^{N=1} \ln \frac{m_2}{m_{susy}} + \beta_2 \ln \frac{m_{susy}}{m_Z}, \quad (2)$$

$$\alpha_3^{-1}(m_Z) = \alpha_X^{-1} + \beta_3^{N=2} \ln \frac{M_X}{m_2} + \beta_3^{N=1} \ln \frac{m_2}{m_{susy}} + \beta_3 \ln \frac{m_{susy}}{m_Z}. \quad (3)$$

N=2 SUSY			N=1 SUSY			NON-SUSY		
$2\pi\beta_3^{N=2}$	$2\pi\beta_2^{N=2}$	$2\pi\beta_1^{N=2}$	$2\pi\beta_3^{N=1}$	$2\pi\beta_2^{N=1}$	$2\pi\beta_1^{N=1}$	$2\pi\beta_3$	$2\pi\beta_2$	$2\pi\beta_1$
6	10	22	-3	1	11	-7	-19/6	41/6

Table 1: This table gives beta coefficients without the U(1) normalization factor. When we divide columns 3,6,9 by 5/3 we get, 66/5, 33/5 and 41/10 which are well-known values in SU(5) case.

Here α_X^{-1} is the inverse of unified coupling, κ is the $U(1)$ normalization factor, which is usually taken as $\frac{5}{3}$ valid for the $SU(5)$ case, but could be different as well in string models, and the beta coefficients without U(1) normalizations are listed in Table 1.

Let us use canonical normalization $\kappa = \frac{5}{3}$, and the values of three gauge couplings at the scale m_Z to be $\alpha_1(m_Z) = 0.01688$, $\alpha_2(m_Z) = 0.03322$, and $\alpha_3(m_Z) = 0.118$. We solve three simultaneous equations Eqn. 1-3 for three unknowns. The unknowns are $\alpha_X^{-1}, \ln\frac{m_2}{m_{susy}}, \ln\frac{M_X}{m_2}$. After solving we find that,

$$\alpha_X^{-1} = 22.42 - 0.48 \ln\frac{m_{susy}}{m_Z}, \tag{4}$$

$$\ln\frac{m_2}{m_{susy}} = 31.00 - 1.75 \ln\frac{m_{susy}}{m_Z}, \tag{5}$$

$$\ln\frac{M_X}{m_2} = 2.98 + 0.79 \ln\frac{m_{susy}}{m_Z}. \tag{6}$$

Because $m_2 > m_{susy}$, $\ln\frac{m_2}{m_{susy}}$ has to be non-negative. Therefore, from Eqn. 5 we see that $\ln\frac{m_{susy}}{m_Z}$ has an absolute upper bound at $31.00/1.75 = 17.71$. Using the value $m_Z = 91.2$ GeV we find that

$$m_{susy} < 4.48 \times 10^9 \quad \text{GeV}. \tag{7}$$

This upper bound depends on the value of $\alpha_3(m_Z)$. We have plotted this upper bound in solid black line Fig. 1 for values of $\alpha_3(m_Z)$ in the range $0.11 - 0.13$ and for the canonical U(1) normalization of $\kappa = 5/3$. For the central value of $\alpha_3(m_Z) = 0.118$, and m_{susy} at its upper limit, we get $\alpha_X^{-1} = 12.10, M_X = 1.02 \times 10^{17}$ GeV. For $m_{susy} \approx m_Z$, we get, for $\alpha_3(m_Z) = 0.118$, three solved quantities to be, $\alpha_X^{-1} = 20.42, m_2 = 2.6 \times 10^{15}$ GeV and $M_X = 5.1 \times 10^{16}$ GeV. Consequently, we see that, we reproduce results obtained by AEL in the special case of $m_Z \approx m_{susy}$ as expected.

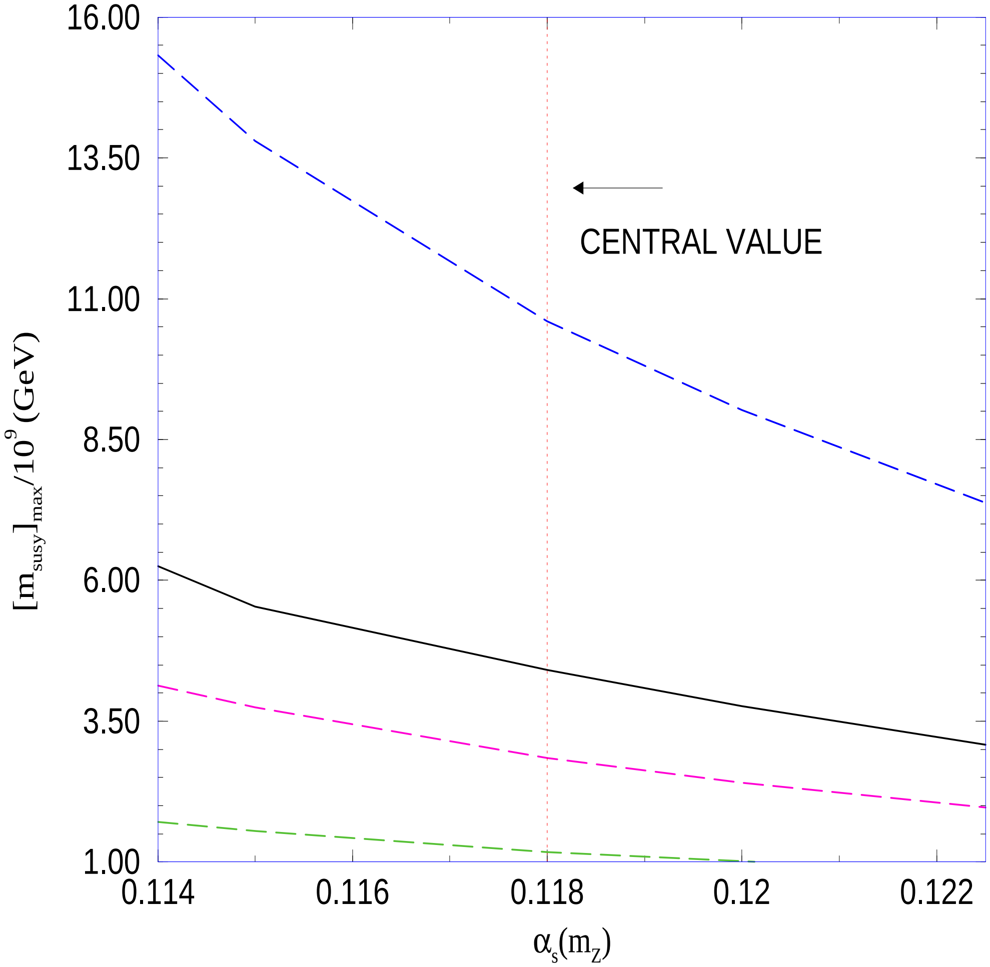

Figure 1: Upper bound on m_{susy} for canonical U(1) normalization. Dashed magenta line shows effects of threshold corrections when wino and gluino thresholds are one order of magnitude higher than m_{susy}. Blue dashed line is the case where wino mass is the same as m_{susy} but gluino mass is higher than m_{susy} by one order of magnitude. Green dashed line is the case when gluino mass is the same as m_{susy} but wino mass is larger by one order of magnitude.

Now let us discuss low energy threshold effects and how it may influence our results. To see this let us recast the RGE and include two more thresholds, namely the, $M_{\tilde{g}}$ and $M_{\tilde{w}}$. These two are the most important supersymmetric thresholds because the gauge contribution to beta function coefficients dominates over fermion contribution and Higgs contribution. Evolution of α_1 remains unaffected at one-loop because it does not have to cross any new threshold. When threshold effect is present $M_{\tilde{g}}$ and $M_{\tilde{w}}$ are different from the common mass scale m_{susy}. Unfortunately we do not know how different they actually are. We can use a few representative cases only. The RGE now becomes,

$$\begin{aligned}
\alpha_2^{-1}(m_Z) &= \alpha_X^{-1} + \beta_2^{N=2}\ \ln\frac{M_X}{m_2} + \beta_2^{N=1}\ \ln\frac{m_2}{m_{\tilde{w}}} + (\beta_2^{N=1} - \Delta_w)\ \ln\frac{m_{\tilde{w}}}{m_{susy}} \\
&\quad + \beta_2\ \ln\frac{m_{susy}}{m_z}, \qquad (8)\\
\alpha_3^{-1}(m_Z) &= \alpha_X^{-1} + \beta_3^{N=2}\ \ln\frac{M_X}{m_2} + \beta_3^{N=1}\ \ln\frac{m_2}{m_{\tilde{g}}} + (\beta_3^{N=1} - \Delta_g)\ \ln\frac{m_{\tilde{g}}}{m_{susy}} \\
&\quad + \beta_3 \ln\frac{m_{susy}}{m_Z}. \qquad (9)
\end{aligned}$$

We will use $\Delta_g = 2$ and $\Delta_w = 4/3$. An easy way to see these numbers is the following. In the non-supersymmetric cases gauge contribution to $SU(3)$ and $SU(2)$ beta functions are -11 and $-22/3$ respectively. If we add to them the gluino contribution $\Delta_g = 2$ and wino contribution $\Delta_w = 4/3$ we get -9 and -6 which are gauge contributions in the supersymmetric case. Using values given in Table 1, now we get,

$$\begin{aligned}
2\pi(\beta_3^{N=1} - \Delta_g) &= -5 \qquad (10)\\
2\pi(\beta_2^{N=1} - \Delta_w) &= -\frac{1}{3} \qquad (11)
\end{aligned}$$

Furthermore let us use two more identities,

$$\ln\frac{m_2}{m_{susy}} = \ln\frac{m_2}{m_{\tilde{w}}} + \ln\frac{m_{\tilde{w}}}{m_{susy}} = \ln\frac{m_2}{m_{\tilde{g}}} + \ln\frac{m_{\tilde{g}}}{m_{susy}} \qquad (12)$$

Then the RGE can be rewritten as,

$$\alpha_2^{-1}(m_Z) = \alpha_X^{-1} + \beta_2^{N=2}\ \ln\frac{M_X}{m_2} + \beta_2^{N=1}\ (\ln\frac{m_2}{m_{susy}} - \ln\frac{m_{\tilde{w}}}{m_{susy}})$$

$$
\begin{aligned}
&+(\beta_2^{N=1}-\Delta_w)\ \ln\frac{m_{\tilde{w}}}{m_{susy}}+\beta_2\ \ln\frac{m_{susy}}{m_z}, &(13)\\
\alpha_3^{-1}(m_Z) \;=\;& \alpha_X^{-1}+\beta_3^{N=2}\ \ln\frac{M_X}{m_2}+\beta_3^{N=1}\ (\ln\frac{m_2}{m_{susy}}-\ln\frac{m_{\tilde{g}}}{m_{susy}})\\
&+(\beta_3^{N=1}-\Delta_g)\ \ln\frac{m_{\tilde{g}}}{m_{susy}}+\beta_3\ln\frac{m_{susy}}{m_Z}. &(14)
\end{aligned}
$$

Now let us define two threshold parameters (σ_w, σ_g) which vanish in the limit $m_{susy} = m_{\tilde{w}} = m_{\tilde{g}}$.

$$
\ln\frac{m_{\tilde{w}}}{m_{susy}}=\sigma_w,\quad \ln\frac{m_{\tilde{g}}}{m_{susy}}=\sigma_g, \tag{15}
$$

Magnitude of these parameters are roughly of the order of $\ln_e 10 = 2.302$ when the gluiono and wino masses differ from m_{susy} by one order of magnitude. Then we get corrected RGE after threshold corrections using Eqn. 10, 11, 15,

$$
\begin{aligned}
\alpha_2^{-1}(m_Z) \;=\;& \alpha_X^{-1}+\beta_2^{N=2}\ \ln\frac{M_X}{m_2}+\beta_2^{N=1}\ (\ln\frac{m_2}{m_{susy}}-\sigma_w)\\
&+\beta_2\ \ln\frac{m_{susy}}{m_z}-\frac{\sigma_w}{6\pi}, &(16)\\
\alpha_3^{-1}(m_Z) \;=\;& \alpha_X^{-1}+\beta_3^{N=2}\ \ln\frac{M_X}{m_2}+\beta_3^{N=1}\ (\ln\frac{m_2}{m_{susy}}-\sigma_g)\\
&+\beta_3\ln\frac{m_{susy}}{m_Z}-\frac{5\sigma_g}{2\pi}. &(17)
\end{aligned}
$$

These equation reduce to Equations 2, 3 in the limit of $\sigma_w \to 0, \sigma_g \to 0$. So we will solve Equations 1,16,17 to get threshold corrections on our bound. From Fig. 1 we see the results. For $\alpha_s = 0.118$ four representative cases can be compared. (i) When all superpartners are degenerate at m_{susy} we get the bound at 4.5×10^9 GeV. (ii) When both gluino as well as wino thresholds are one order of magnitude larger than m_{susy} the bound becomes 2.85×10^9 GeV. (iii) When the wino mass is degenerate with m_{susy} but the gluino mass is one order of magnitude larger then the bound is 1.06×10^{10} GeV. (iv) When the gluino is degenerate with m_{susy} but the wino mass is one order of magnitude larger the bound becomes 1.18×10^9 GeV. So we see that the bound remains stable in the same ball-park region of $10^9 - 10^{10}$ GeVs when threshold effects are included. The upper bound is smeared due to threshold correction. This is not surprising as we know that threshold corrections have

a very similar smearing effect on the mass scales such as the unification scale or intermediate scale of all supersymmetric GUTs.

The upper bounds diplayed on Fig 1. should undergo further small corrections when threshold effects at the N=2 supersymmetry breaking scale is included. We have not considered heavy threshold effects in the text because it is beyond the scope of present letter. But a general observation is that when the spread of n=2 superpartner masses are near the scale m_2 the bound will remain more or less stable near the values given in Fig 1. The theoretical reason behind it is that the mass scales in the RGE enters only through natural logarithms. Therefore the results do not get much affected by small fluctuations in individual masses near about the scale m_2. Note that only new particles beyond standard model those are included in this analysis have their origin in $N = 1$ and $N = 2$ supersymmetry. Therefore their masses must be tied to the scales m_{susy} and m_2 and fluctuation will remain under control.

Another possiblility is the existance of ad-hoc new thresholds such as exotic particles between M_X and m_z which are completely unrelated to N=1 and N=2 supersymmetry. Their masses will therefore be completely unrelated to m_{susy} or m_2. They may change the upperbound considerably. But here we have not considered exotic new particles which are not predicted by $N = 1$ or $N = 2$ supersymmetry.

Furthermore we would like to comment on extra vector-like exotic matter those may exist anywhere in between M_X and m_{susy}. Such vector-like matter may get masses from the Giudice-Masiero [43] type mechanism which is often used to get the mass of the $\mu\ H_1\ H_2$ term. Their existence will change the beta functions and alter the present RGE analysis. Therefore the existence of such extra vectorlike matter will also change the upper bounds quoted in this paper. Because we have worked on the minimal version of $N = 2$ supersymmetry, we have not considered exotic vector-like matter either.

Now let us discuss briefly how this upper bound on m_{susy} can be changed. If we take the canonical value of $\kappa = 5/3$ results of Fig. 1 are obtained. If we notice numerical values of $U(1)_Y$ beta functions we will realize that electric charge is defined as,

$$Q = T_L^3 + \sqrt{\frac{5}{3}}Y. \tag{18}$$

This is a consequence of the fact that all charges of matter multiplets are normalized under either $SU(3)$ or $SU(2)_L$ or $U(1)_Y$ in a similar manner.

The underlying assumption being that the generators of $SU(3)$ or $SU(2)_L$ or $U(1)_Y$ are unified as generators of a bigger unified gauge group. This is a natural demand if we want gauge coupling unification as some scale below the mass scale of string theory. If this is not the case, and string theory breaks directly to $SU(3)_3 \times SU(2)_L \times U(1)_Y$ without passing through an unified gauge theory just below string scale, the charge relation need not have the factor $\sqrt{\frac{5}{3}}$ [35, 36, 37, 38, 39] and the general string inspired unification condition then reads,

$$K_3\ \alpha_3 = K_2\ \alpha_2 = K_Y\ \alpha_1. \tag{19}$$

Let us choose $K_3 = K_2 = 1$ and $K_Y \neq 1$. Then the upper-bound can be changed. If we take a sample value of $K_Y = 17/3$, then in this string inspired model, electric charge is defined as,

$$Q = T_L^3 + \sqrt{\frac{17}{3}}Y, \tag{20}$$

and, corresponding solution of mass scales reads as,

$$\alpha_X^{-1} = 2.04222 - 0.0477465 \quad \ln\frac{m_{susy}}{m_Z}, \tag{21}$$

$$\ln\frac{m_2}{m_{susy}} = 18.1579 - 1.45 \quad \ln\frac{m_{susy}}{m_Z}, \tag{22}$$

$$\ln\frac{M_X}{m_2} = 15.8149 + 0.491667 \quad \ln\frac{m_{susy}}{m_Z}. \tag{23}$$

From Eqn. 22 we see that to keep $\ln\frac{m_2}{m_{susy}}$ non-negative we have to have $\ln\frac{m_{susy}}{m_Z}$ less than 12.5227, which gives $m_{susy} < 2.50 \times 10^7$. So the bound on m_{susy} given in Eqn. 7 is changed by two orders of magnitude. Also note that for $\ln\frac{m_{susy}}{m_Z} = 0$ one get $\alpha_X = 0.4896, m_2 = 7.01 \times 10^9, M_X = 5.17 \times 10^{16}$ thus correctly reproducing numbers quoted by AEL (c.f. Table 3 row 1 of AEL) for the special case of $m_Z = m_{susy}$.

Let us now discuss two relevent points regarding this letter. (i) This is a $N = 2$ supersymmetric model broken to $N = 1$ supersymmetric model. This may look unfamiliar. However whenever we work on supersymmetric unification we assume that there is string theory at some scale above the GUT scale. String theory predicts $N = 4$ supersymmetry. So at some stage $N = 4$ supersymmetry has to break to $N = 2$ supersymmetry which will

then break to $N = 1$ supersymmetry. (ii) The upper bound is very high, which is not attainable at foreseeable future. This seemingly uninteresting result is relevant for the following reason. There are plans to probe $N = 1$ supersymmetric particle content in future experiments. Let us assume that we want to search superpartners at the scale of 40 TeV. We may ask that is that too high a scale to search for superpartners if $N = 2$ supersymmetry breaks to $N = 1$? We have given the answer to that here which states that in the class of models where the symmetry breaking chain is $N = 2 \to N = 1$, if superpartners exist at (say) 40 TeV, they will not conflict with gauge coupling unification. Our result also says that if $N = 1$ supersymmetry is broken at a scale higher than 6.35×10^9 GeV, we will not achieve gauge coupling unification.

In conclusion, we have generalized the analysis of AEL by separating two scales m_Z and m_{susy}. In the paper of AEL the question that was asked was how much one can lower the scale m_2 which is the scale of $N = 2$ breaking and also what other relevant constraints can be imposed upon m_2. In the present analysis we ask the question, how high the scale m_{susy} can be in that context by unlocking to scales m_Z and m_{susy} which were assumed to be equal in the analysis of AEL. This analysis is in some sense complementary to the analysis of AEL. The scale m_{susy} is very important from the point of view of experiments. This is because in experiments we search for superpartners of standard model particle at around the scale m_{susy}. In principle m_{susy} can be as high as the Planck scale[40, 41, 42], ie, all superpartners become massive at Planck scale and below Planck scale there is non-SUSY standard model. In such a case, present day experiments will not be able to trace any superpartner. This is the reason why any theoretical or experimental upper bound or lower bouund[44] on the scale m_{susy}, that may exist, should be explored.

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